

A New Code Simulates the Cosmos

A Livermore astrophysicist's code can model almost anything from a small black hole to the entire universe.

BY day, Livermore astrophysicist Peter Anninos works on stockpile stewardship projects. Many astrophysicists at Lawrence Livermore work primarily in the weapons program to safeguard the reliability of the nuclear stockpile because the two fields have so much in common: the fusion process that powers stars is the same one that unleashes the deadly energy of a thermonuclear weapon. "Astrophysics is about as close to Weapons 101 as you can get in college," he says.

But Anninos's first love is cosmology, the evolution of the universe. In his spare time, he began to develop a new computer code he called COSMOS to simulate an unprecedented variety of astrophysical events in one, two, or three dimensions.

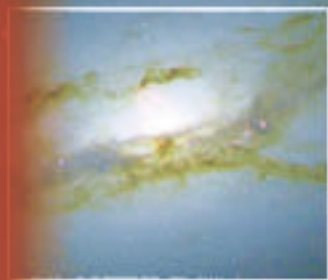
Anninos had only bits and pieces of the COSMOS code finished until about a year ago, when astrophysicist Stephen

Murray instigated the hiring of Chris Fragile as a postdoctoral fellow to perform astrophysics research full time. Fragile, who transformed a fascination with black holes into a career in astrophysics, has fleshed out the code with Anninos and performs most computer runs.

Now virtually complete, COSMOS can model almost anything from a small black hole to the entire universe. (See the box on p. 7.) It has already been applied to an ambitious array of astrophysical problems: the evolution of the very early universe, accretion of matter by black holes, star formation, and the evolution of dwarf galaxies.

The Universe in Transition

The young universe was a hot, dense "foam" of quantum fields until moments after the big bang, when it began to expand. About 300,000 years



later, hydrogen atoms first appeared when temperatures had cooled enough for electrons and nuclei to join. Hundreds of millions of years later, matter began to come together to form stars and galaxies. (See the **box on p. 8.**)

Anninos recently used COSMOS to model one of the phase transitions that took place just after expansion began, when the universe was about a hundred-thousandth of a second old. During this transition, the most fundamental forms of matter—quarks and gluons—joined to become protons and neutrons. Because particles that contain three quarks, including protons and neutrons, are known collectively as hadrons, this event is known as the quark–hadron phase transition. While a few other researchers have examined early cosmology in one spatial dimension, Livermore’s simulations of the quark–hadron transition are the first in multiple dimensions.

In the universe of today, matter is spread haphazardly in clumps with vast areas of some unknown substance—perhaps dark matter—in between. Astrophysicists surmise that the manner in which the early phase transitions took place may be the cause of this unevenness. These phase transitions may also have given rise to a population of primordial black holes and may have set the foundation for the production of galactic and extragalactic magnetic fields.

“If the quark–hadron phase transition were turbulent,” says Anninos, “the universe would be more homogeneous today. We wanted to find out how stable—or unstable—the transition boundaries were to flow perturbations and shock collisions. We also wanted to determine whether destabilizing mechanisms play a role in how hadrons evolve and mix.”

It is possible that bubbles and droplets of varying phases may have coexisted for a time, resulting in an uneven production and distribution of hadrons. The simulation shown in the figure below illustrates how these bubbles may have behaved as a wall of hadronic material collides with an isolated bubble of hadrons. The background is initially composed of supercooled quark material. But the expanding hadronic regions quickly convert quarks into hadrons immediately behind a detonation or shock front. However, as shocks pass through the cooled hadron regions, they reheat the hadrons. Reheating may either decompose the hadrons back into their quark constituents or simply impart a spectrum of thermal fluctuations to the hadrons. The simulations provide clear evidence of the formation of quark “nuggets” that may still survive today in the form of dark matter.

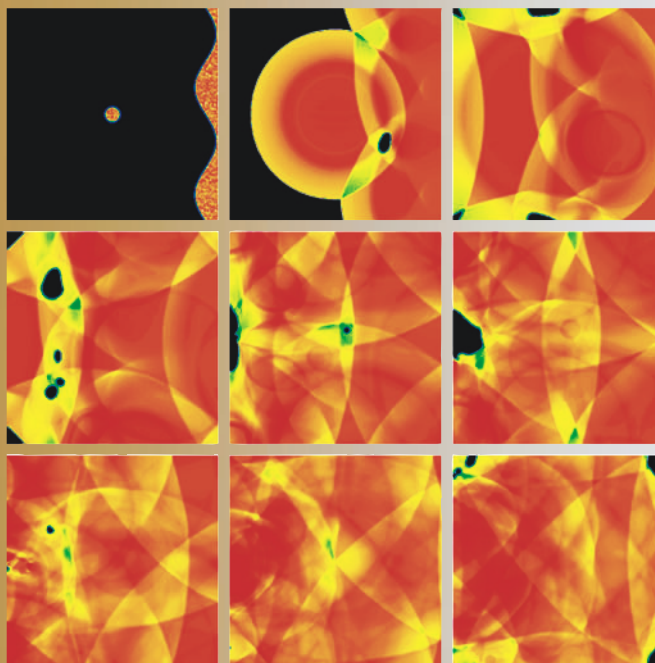
Although the team’s simulations to date show complex behavior, there is no evidence of hydrodynamic turbulence during this transition period, at least for the cases they investigated.

The Tug of Black Holes

Black holes tugged at Chris Fragile’s imagination when he was younger. Black holes also tug madly at anything that comes within their gravitational field, sucking in dust, gas, and even stars. According to the general theory of relativity, black holes drag space–time around them in a spiraling whirlwind.

Although a black hole itself is not visible, hot matter that orbits around it is. The gases closest to the black hole are very hot and emit x rays. Further away from the black hole, cooler material emits visible radiation.

Black holes are suspected to exist in the center of all galaxies. In October



In this simulation, a wall of cold hadronic material collides with an isolated bubble of hadrons. Although the background is initially composed of supercooled quarks, the expanding hadronic regions quickly convert quarks into hadrons immediately behind the detonation or shock front. There is also clear evidence of the formation of quark “nuggets” (the dark spots) that potentially may have survived to the present as dark matter.

2002, scientists reported having found strong evidence for a dense black hole more than two million times as massive as our Sun in the center of the Milky Way Galaxy. After tracking the paths of several stars in the vicinity of the presumed black hole for 10 years, they discovered at least one star in an orbit that may send it to its death in the black hole in about 15 years. Another indicator of the presence of a black hole is the speed with which things move. In our galaxy, most objects move at about 100 kilometers per second. Near black holes, however, they may move as fast as 9,000 kilometers per second.

Fragile is modeling single rotating black holes with a disk or torus of gas being sucked into them, a process known as accretion. The topmost figure below shows a model of an accreting gas torus around a black hole. In one version, a black hole has its spin axis aligned with the angular momentum axis of the torus. Although they are spinning in opposite directions (180 degrees from each other), the black hole accretes the most material from the torus in this position.

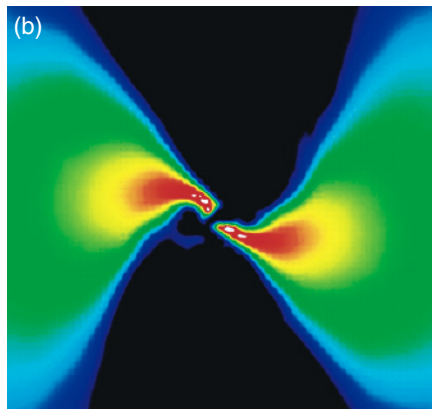
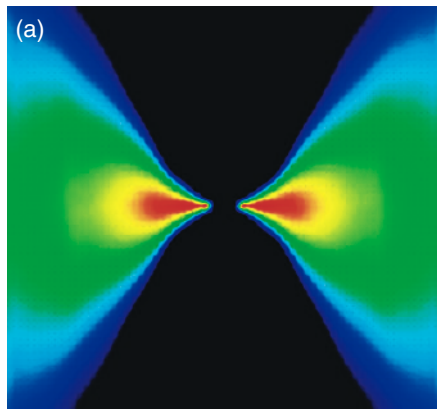
In another version, the spin axis is tilted 30 degrees relative to the angular momentum axis of the same accreting

gas torus. No one has modeled such a tilted black hole torus before, although they are expected to exist in nature.

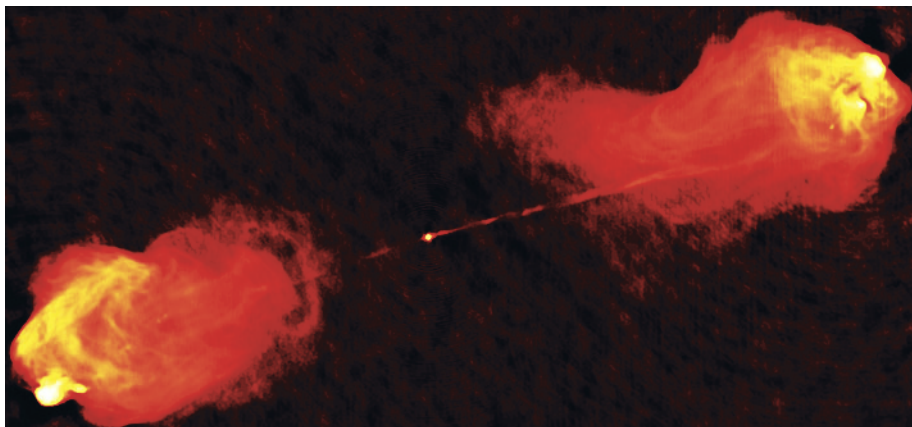
The tilt angle produces important differences in the geometry of the accretion pattern, particularly close to the black hole. Here, spiraling space-time produces what is known as frame dragging, a general relativistic effect, which causes the shape of the torus to warp. Frame dragging also affects how much of the gas can eventually be captured by the black hole, which in turn will affect how bright the system's x rays are.

For constructing the model, COSMOS currently uses a three-dimensional Cartesian mesh, which has a uniform grid of zones that describe discrete elements of the model. "To have enough zones to get far out in the torus, we end up with just a few around the black hole," Fragile says. "That means the resolution around the black hole isn't as good as we would like."

One solution is to add zones at the black hole without adding them further out in the torus, creating a nonuniform grid. The other is to create a spherical grid, which would resemble a globe with the black hole at the center. But modeling in this way is difficult, especially near the boundaries of the black hole where gravity is strongest. The challenges never stop.



(a) Simulation of the spin axis of a black hole aligned with the angular momentum axis of the torus. (b) The black hole spin axis is tilted 30 degrees relative to the angular momentum axis of the same accreting gas torus. No one had modeled a tilted black hole torus such as this before. The tilt produces major differences in how the black hole accretes matter.



A radio telescope reveals this image of high-energy radio jets coming from a massive black hole.

Cosmic Fireworks

Black holes don't just pull cosmic junk in. They also spit it out. For decades, astronomers have observed massive rotating black holes in the centers of some huge elliptical galaxies that spew high-energy jets, as shown in the figure at left. These narrow streams of high-velocity particles emit radiation in the form of radio waves, but their exact nature and how they interact with their surroundings remain a mystery.

In 1985, before he came to Livermore, astronomer Wil Van Breugel led a team studying whether a radio jet emanating from elliptical galaxy NGC 541 was interacting with a cooler cloud of gas and causing the formation of stars. Such an event is known as a jet-induced starburst. His team used radio and optical imaging as well as optical spectroscopy to compare emissions from NGC 541 with emissions from a confirmed prototypical starburst galaxy.

“The idea of a jet triggering a starburst in a cloud made news,” says Van Breugel. “But many scientists

didn’t believe it at the time. It seemed too much like science fiction.”

At the time, many thought the gas might be part of a preexisting galaxy that happened to be nearby. Furthermore, it was unclear if it was even possible for a jet to trigger the collapse of a gas cloud.

More recently, much more sensitive observations by Van Breugel and others using the Hubble Space Telescope and the Keck Observatory on Mauna Kea, Hawaii, indicate that jet-induced star formations do indeed occur and may even have been a common phenomenon in the early

universe when galaxies were forming. In young galaxies, much of the gas has yet to form into stars. Jets may help this process by pushing gas clouds to higher densities, forming stars a bit sooner than they would if only gravitational forces acted. In powerful jets, star formation is probably initiated by shocks that move sideways, along the edge of the jets.

“Understanding this process of jet-induced star formation requires numerical simulations with complex, multidimensional computer codes such as COSMOS,” says Van Breugel. A COSMOS simulation of jet-cloud

Inside COSMOS

Given Peter Anninos’s interest in cosmology, COSMOS is an appropriate name for the code he developed. When Anninos first began work on it, he was hoping to simulate such isolated phenomena as black holes and neutron stars in three dimensions. These all require modeling nonlinear interactions between different sources of matter and highly relativistic gravitational fields.

COSMOS is unusual in being easily adaptable to either relativistic or Newtonian astrophysical phenomena. The exceedingly strong gravitational fields in effect immediately after the big bang, during the initial inflation of the universe, and near black holes are governed by the laws of relativity. In contrast, classical Newtonian physics governs cosmological and astrophysical events that occur in the presence of much weaker gravitational fields. Examples include the creation of stars and galaxies during which gravity behaves in a fashion more familiar to us.

The general and special theories of relativity provide a unified description of space and time as a single continuous fabric called space-time. The general theory also describes gravity through the notion of “curved” space-time and governs the motion of all objects in the presence of this curvature. For instance, general relativity predicts that when a large enough mass is concentrated in

a small enough volume, that mass distorts the space around it so much that a part of space wraps itself up and leaves the rest of normal space behind. This is a black hole. Anything that falls into the black hole—including light—can never get out.

Codes that can simulate relativistic flows in the presence of ultrastrong gravitational fields have been around for some time, but each has been “tuned” to a particular purpose, such as modeling black hole dynamics, cosmological gravitational waves, or binary neutron stars. COSMOS, in contrast, is designed for generic applications so that with only minor modifications, it can simulate a variety of events.

Astrophysics models are very computationally intensive. COSMOS could have only been developed at an institution such as Lawrence Livermore with its massively parallel terascale computers. To date, the code has run successfully on several different Livermore computers.

“Most astrophysical problems are inherently multidimensional,” notes Anninos, so he designed COSMOS to run in up to three dimensions. It currently uses a uniform mesh, composed of quadrilateral-shaped zones in two dimensions and hexagonal-shaped zones in three. Although all calculations that have been run to date use Cartesian coordinate systems, the code can be adapted to curvilinear meshes as well.

How the Universe Started

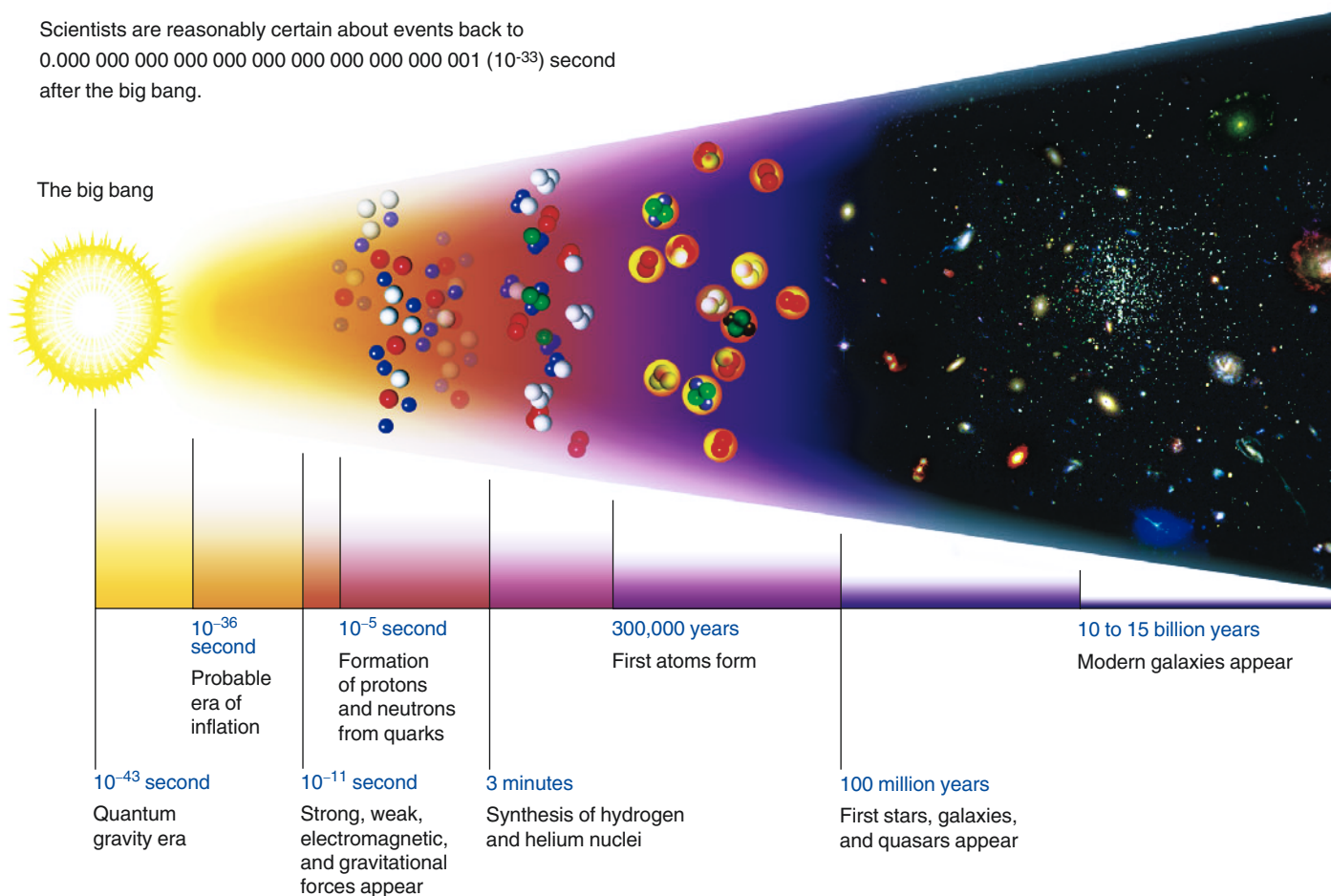
The Standard Model of cosmology says that the big bang happened about 15 billion years ago. In the first moments after that cataclysmic event, the universe was still a single hot, dense entity in which all the forces we know today—the strong, electromagnetic, weak, and gravitational—were unified. In the first hundred-billionths of a second after the big bang, the four forces came into being, one by one, in a series of rapidly occurring phase transitions.

The most elementary particles—quarks and gluons—briefly floated freely. But during the final phase transition of the early universe, at about a hundred-thousandth of a second after the big bang, they became bound together to form the protons and neutrons that make up ordinary matter today. Three minutes after the big bang, protons and neutrons first formed nuclei of hydrogen and helium in a process known as nucleosynthesis. The universe

was 300,000 years old before electrons and nuclei joined to form any atoms heavier than a simple proton–neutron hydrogen atom. All heavier elements—nitrogen, oxygen, iron, copper, and so on—were created much later in stars, which began to develop when the universe was 100 million to about 1 billion years old.

At the time of electron–nuclei combination, the radiation temperature of the universe was about 3,000 kelvins. The universe has expanded and cooled since then such that its radiation temperature today is just 3 kelvins. This temperature corresponds to that of the microwave radiation that rains down upon us today from all directions, radiation that has been traveling through the universe since it decoupled from matter. This radiation is just one of many clues that have allowed scientists to solve the puzzle of how the universe got started.

Scientists are reasonably certain about events back to 0.000 000 000 000 000 000 000 000 001 (10^{-33}) second after the big bang.



interactions, using temperature, density, and velocity data estimated from observed systems such as NGC 541, is shown in the leftmost figure below. Livermore's simulations are the first ever to incorporate cooling, a critical component of the process of star formation.

Van Breugel wants to use COSMOS to help answer a number of questions: What is the range of jet and shock velocities that allows the clouds to collapse rather than heat up and disperse? What are the required densities and temperatures of the gas in the star-forming clouds? What is the chemical composition of the clouds, that is, how important is the cooling efficiency of the gas? These answers will provide valuable insight into the nature of the jets themselves and the physical conditions in galaxies as they form.

These new calculations may also help to determine whether feedback from active jets, emanating from the vicinity

of black holes, helps or hinders the growth of galaxies. A few years ago, scientists discovered that the masses of black holes and their parent galaxies are closely related, making the feedback mechanism an important issue in astrophysics today.

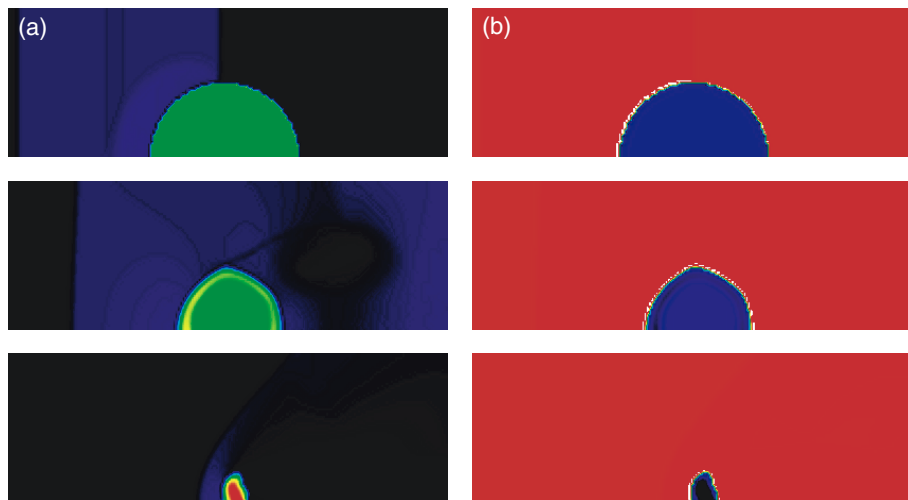
Galactic Building Blocks

Astrophysicist Stephen Murray, like Anninos, is primarily a weapons physicist. But, together with colleagues at the University of California at Santa Cruz, he obtained funding from the National Aeronautics and Space Administration to study dwarf spheroidal galaxies, which orbit much more massive galaxies.

"Dwarf galaxies were most likely the first galaxies to form in the early universe," Murray says. "They are likely the building blocks of larger galaxies. So the number of dwarf galaxies we observe today are probably the remnants of a much larger initial

population, most of which went to form our own galaxy. These survivors make excellent laboratories for studying how stars form in the early universe and may tell us something about the early evolution of more massive galaxies."

Because dwarf spheroidal galaxies are the smallest type of dwarf galaxy, one might expect them to be simple laboratories for studying star formation. But astronomers find that they exhibit a variety of histories. Some show evidence of only a single burst of star formation while others show signs of having had multiple bursts. Yet others appear to have had more or less continuous star formation over their lifetimes. Some contain differing amounts of heavy elements, while others show little variation from star to star. Understanding the reasons for such variety requires looking at the many factors that affect dwarf spheroidal galaxies. Murray and Fragile have used COSMOS to simulate two phenomena



For star formation to occur, a cloud of gas must first cool enough for hydrogen molecules to begin to form. As the cloud cools, it will also become denser. This simulation shows some of the early steps in the cooling and condensing process caused by the interaction of a radio jet with a cloud of gas. The jet is not visible because it is larger than the cloud and covers the whole grid. (a) Over a span of 1.4 million years, the cloud of gas increases in density by a factor of 1,000. (b) At the same time, the temperature of the cloud of gas cools from 5,000 kelvins to less than 800 kelvins.



Dwarf spheroidal galaxies are not very photogenic. Here, the Pegasus dwarf spheroidal galaxy is hiding among brighter stars. (Keck Observatory image, courtesy of P. Guhathakurta, University of California at Santa Cruz.)

in these galaxies that relate to their evolution: enrichment and tidal stripping.

Enrichment is the process by which elements heavier than helium are created and dispersed into the universe. Most such elements are formed by nuclear fusion within the cores of stars much more massive than the Sun. When these stars die, they explode as supernovas, dispersing the elements they have created into space. The heavy elements are then mixed into the galactic gas from which a subsequent generation of stars may form. Only through countless stellar deaths over the millennia have there come to be elements heavier than helium in amounts comparable to those seen in the Sun.

Murray and Fragile examined the ability of dwarf spheroidal galaxies to

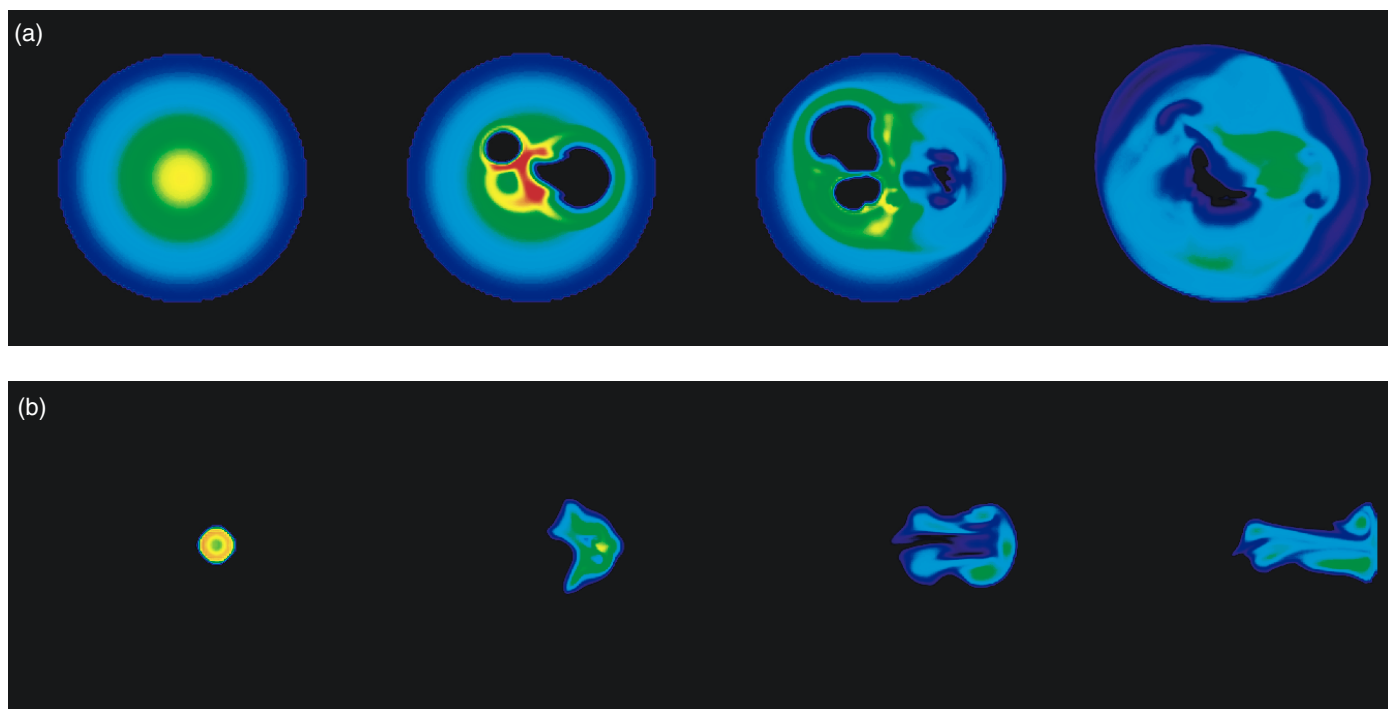
retain gas expelled by supernovas. Simulations with COSMOS examined the effects of multiple supernova explosions at random locations throughout the cores of dwarf galaxies. A three-dimensional code was essential because no assumptions could be made about the symmetry of the system.

The simulations showed for the first time how supernova gases can “chimney” their way out of the galaxy without mixing with galactic material. This effect may explain why some dwarf spheroidal galaxies have less heavy-element enrichment than would be expected from their history of star formation. The material ejected from supernovas in dwarf galaxies would almost certainly be captured by massive galaxies that form after the dwarfs. Such preenrichment may help

to explain why astronomers studying our own Milky Way Galaxy find very few stars lacking in heavy elements.

Factors external to the dwarf galaxy may also explain their evolution. Tidal stripping is a process whereby massive galaxies strip material from their smaller neighbors. This transfer of mass to the larger galaxy is a galactic-scale version of black hole accretion. “Big galaxies make bad neighbors,” says Murray with a smile.

His team modeled a dwarf galaxy under the influence of a larger nearby galaxy. If its gas is ionized and heated, either by external or internal sources, then the gas may be rapidly lost from the system, preventing the formation of subsequent generations of stars. The result, in the presence of a massive galaxy, is to limit the ability of the dwarf system to form multiple



(a) Plots reveal the density of gas along slices through the center of an initially undisturbed dwarf galaxy. Following a fairly rapid burst of several supernovas near the center of the galaxy, substantial disturbance of the gas is visible. (b) The concentration of enriched material from the first supernova “chimneys” its way out of the galaxy. This chimneying effect is a new discovery in dwarf spheroidal galaxies and may explain why some such galaxies have less heavy-element enrichment than might be expected.

generations of stars or, in extreme cases, to form any stars at all.

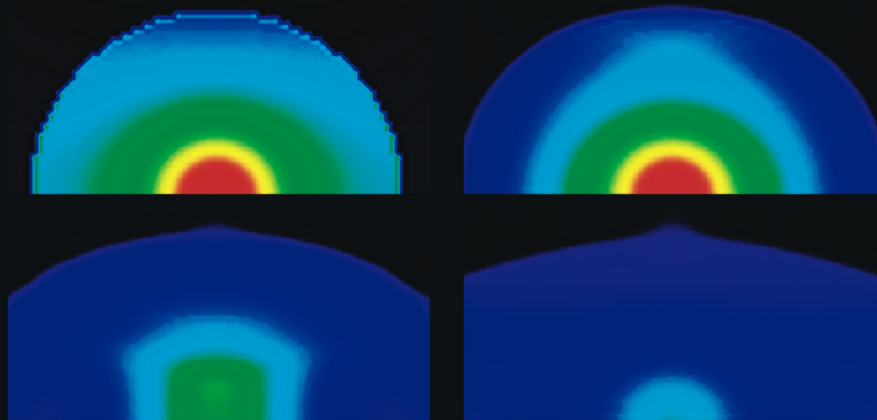
An Expanding COSMOS

As observational data continually improve, astrophysics codes must be able to keep up and include as many physical processes as possible.

"The code is mostly done," says Anninos. "Now we're concentrating on actually using it. But in the next year or two, we'll be adding more physics to it."

He and Fragile plan to add photon transport and neutron diffusion to the code, and they will modify the existing system of equations for radiation chemohydrodynamics to include magnetic fields. To improve the code's accuracy and efficiency for problems requiring varying degrees of spatial resolution—such as the black hole torus simulations—they will add some form of adaptive grid technology to the code.

"COSMOS is just beginning to give us the 'why' and 'how' of astronomers' observations," says Anninos. As



Over the course of 190 million years, a nearby massive galaxy steals material from a dwarf spheroidal galaxy in a process known as tidal stripping.

the code's capabilities are expanded, it will bring observations into ever clearer view.

—Katie Walter

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